Using Loop Heat Pipes to Minimize Survival Heater Power for NASA's Evolutionary Xenon Thruster Power Processing Units

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A thermal design concept of using propylene loop heat pipes to minimize survival heater power for NASA's Evolutionary Xenon Thruster power processing units is presented. It reduces the survival heater power from 183 W to 35 W per power processing unit. The reduction is 81%.

Nomenclature

BAT	=	Burst Alert Telescope
CC	=	compensation chamber
CCHP	=	constant conductance heat pipe
EM	=	engineering model
LHP	=	loop heat pipe
MLI	=	multi-layer insulation
NEXT	=	NASA's Evolutionary Xenon Thruster
NEXT-C	=	NASA's Evolutionary Xenon Thruster-commercial
NSTAR	=	NASA's Solar Electric Propulsion Technology Application Readiness
PPU	=	power processing unit
VCHP	=	variable conductance heat pipe

I. Introduction

NASA's Evolutionary Xenon Thruster (NEXT) project is developing next generation ion propulsion technologies. Fig. 1 shows the NEXT prototype hall thruster in testing at NASA Glenn Research Center (GRC). NEXT has applications for a wide range of NASA's solar system exploration missions. It potentially benefits the Discovery, New Frontiers, Mars Exploration and outer planet missions to reach difficult destinations by reducing the propellant consumption. It may also shorten the mission cruise time by avoiding multiple planet flybys that chemical propulsion needs for a boost.[1]

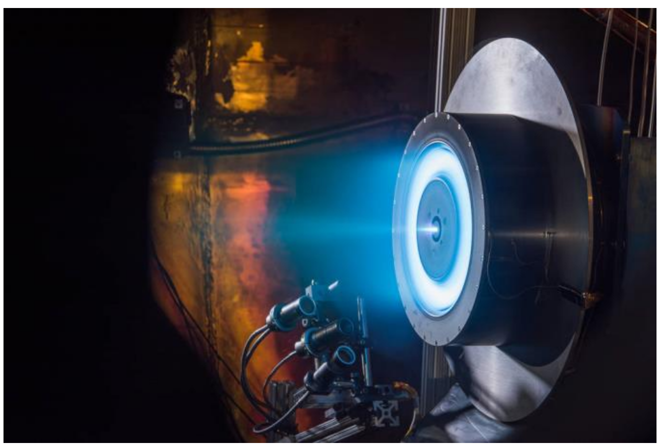

Figure 1. NEXT Prototype Hall Thruster in Testing. (Source: NASA).

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A critical element of NEXT is the power processing unit (PPU), which processes power from solar arrays and converts it to the voltages and currents required for thruster operation. The PPU supplies regulated power to the key components of the thruster. It contains six different power supplies: beam, discharge, discharge heater, neutralizer, neutralizer heater, and accelerator supplies. The beam supply is the largest and processes up to 93% of the power. NASA GRC designed and fabricated an engineering model (EM) PPU for the NEXT project. It is capable of processing from 0.5 to 7 kW of output power for the NEXT ion thruster. Its design includes many significant improvements for better performance over the state-of-the-art NASA's Solar Electric Propulsion Technology Application Readiness (NSTAR) PPU. The most significant difference is the beam supply, which consists of six modules and capable of very efficient operation through a wide voltage range because of innovative features like dual controls, module addressing, and a high current mode. The low voltage power supplies are based on the previously validated NSTAR PPU. The highly modular construction of the PPU resulted in improved manufacturability, simpler scalability, and lower cost.[2,3,4,5] Fig. 2 is a NEXT PPU EM block diagram.[3] Fig. 3 shows the NEXT EM PPU.[6]

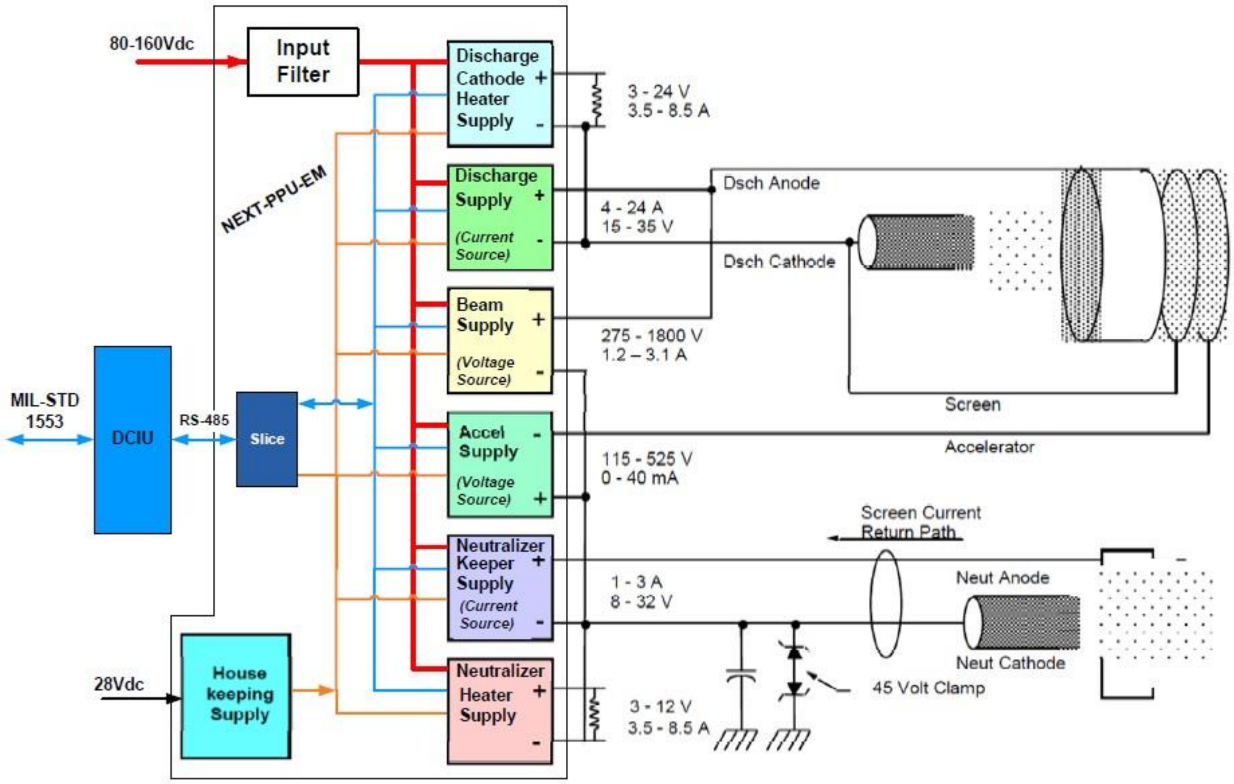

Figure 2. NEXT PPU EM Block Diagram. (Source: NASA).

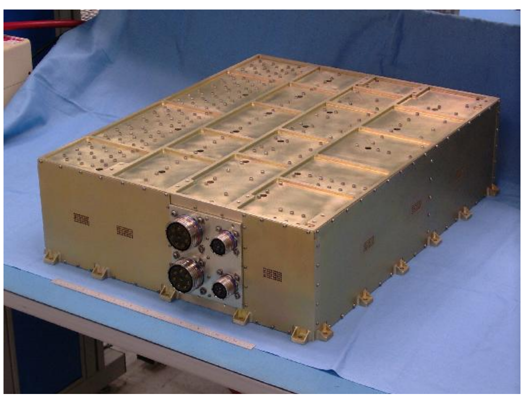

Figure 3. NEXT EM PPU.

NEXT-commercial (NEXT-C) is a NASA contract with Aerojet Rocketdyne to develop the PPU to flight levels and build two sets of thrusters and PPUs. The NEXT-C PPU is derived from the design developed during the NEXT technology project. Design modifications are made to address issues encountered during the technology project and lessons learned.

Efficient conversion of solar array power to thruster power is important in achieving overall ion propulsion system performance. The NEXT PPU accepts unregulated primary power in the 80 V to 160 V range. High voltage benefits high power systems in reducing the current levels and minimize ohmic losses. The PPU efficiency has a significant impact on both the electrical power subsystem and thermal control subsystem of a mission. It varies with input power, input bus voltage, and PPU temperature. A higher efficiency reduces the solar array size required to run a thruster at full power, and reduces the PPU waste heat for thermal management. The PPU efficiency at the full power throttle condition and input bus voltage of 100 V has been demonstrated to be 94.5% at a PPU baseplate temperature of 25°C, and 94.1% at 50°C for the EM PPU.[2,3,4,5]

The NEXT-C PPU is in prototype phase, preparing for qualification level environmental testing. Electrical and mechanical designs are completed. Environmental testing was planned for 2017. Integrated system level test with NEXT-C thruster was planned for late January/early February 2017. Worst case analysis is partially completed, and under review. Flight hardware delivery to NASA is slated to be completed in early 2019. Table 1 lists the existing EM and planned performance characteristics of the NEXT-C PPU.[6,7,8,9] Table 2 is a summary of the thermal requirements for the PPU baseplate, which is the heat sink.

Table 1. Planned Performance Characteristics of PPU.

	Existing EM	Planned
Input Power (W)	630-7260	640-7360
Peak Efficiency (High Voltage Bus)	95%	>93.5%
High Power Input Voltage (V)	82-160	80-160
Housekeeping Input Bus (V)	28	28
Housekeeping Power (W)	16-28	<40
Mass (kg)	33.9	<36.8

Table 2. PPU Thermal Requirements.

	Temperature Limits (°C) at Baseplate	
	Minimum	Maximum
Operating	-20	50
Non-Operating (Survival)	-40	70

II. PPU Thermal Management Issue

The PPU baseplate area is approximately 0.21 m^2. For an input power of 7,360 W and a peak efficiency of 93.5%, the waste heat transferred by conduction to the baseplate is 478 W. After adding a 15% uncertainty margin for worst hot case thermal analysis, the radiator needs to be sized for removing 550 W from the PPU baseplate. The following assumptions are made. The PPU exterior is insulated with multi-layer insulation (MLI). There is no solar or planetary flux incident on the PPU radiator. The PPU radiator has a view factor of 1.0 to space. A1.05 m^2 radiator with Z93C55 conductive white paint is required to maintain the PPU operating maximum baseplate temperature at 40°C. While the PPU is non-operating, 183 W of survival heater power is required to maintain its baseplate temperature above -40°C. If a mission uses three ion thrusters, each thruster will require a PPU. Each PPU will require a 1.05 m^2 radiator and 183 W of survival heater power. The PPU survival heater power, 549 W total for three PPUs, potentially becomes an issue for the mission. If there is solar or planetary flux incident on the radiator when the PPU is operating, the radiator size could be larger and the survival heater power could be higher.

III. Solution for PPU Survival Heater Power Problem

In order to minimize the PPU survival heater power when it is non-operating, the options are to minimize the thermal conductance from the PPU baseplate to its radiator or to minimize the emittance of its radiator to space. A method to minimize the thermal conductance from the PPU to its radiator is to use loop heat pipes (LHPs), which have NASA flight heritage. In addition to heat transport, LHP can also serve as a thermal switch. After it shuts down, there is no heat transfer from the PPU to the radiator. A thermal louver typically has a maximum effective emittance of about 0.7 when it is fully open, and a minimum effective emittance of about 0.12 when it is fully closed. Louver potentially requires a larger radiator than LHP. Using two LHPs provides full redundancy to minimize the probability of a single point failure for a NASA risk Class A or B mission. Redundancy is not possible for thermal louver. A sunshield is needed for a thermal louver, if the radiator can be exposed to sunlight. It further reduces the louver effective emittance. Therefore, LHP is selected for minimizing the PPU survival heater power in this paper.

Fig. 4 shows a thermal block diagram for using two LHPs for temperature control of the PPU. It is derived from the LHP thermal control subsystem on the NASA's *Swift* Burst Alert Telescope (BAT), which has been in successful operation in orbit since November 2004. The LHP working fluid is propylene, which is the same as that for the BAT LHPs. It prevents the freezing problem for the condensers after the LHP shuts down when the PPU is non-operating. In order to provide a heat transport capacity of 621 W, that is 478 W plus 30% margin, the evaporator of each LHP is approximately 3.175 cm diameter and 61 cm long. Constant conductance heat pipes (CCHPs), which have ammonia as the working fluid and 1.27 cm diameters, are attached to the PPU baseplate to transfer heat to the LHP evaporators. Ammonia is acceptable since its freezing point is more than 30°C colder than the minimum non-operating temperature limit of -40°C for the PPU. Like the *Swift* BAT (Fig. 5), the LHP condensers can be attached to the backside of the PPU radiator, which is a machined aluminum panel. Alternatively, they can be embedded in the radiator, which is an aluminum honeycomb with aluminum facesheets. Transport lines transfer heat from the evaporators to the radiator, and from the radiator to the compensation chambers (CCs).

Flexible Kapton heaters can be designed for voltages of 240 V or higher. There is no technical issue with 80 V to 160 V for heaters, mainly used for the LHPs.

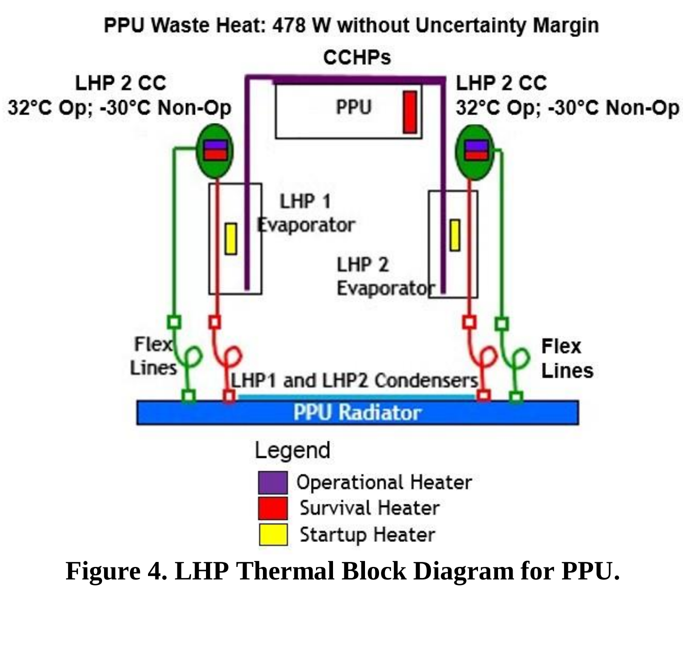

Figure 4. LHP Thermal Block Diagram for PPU.

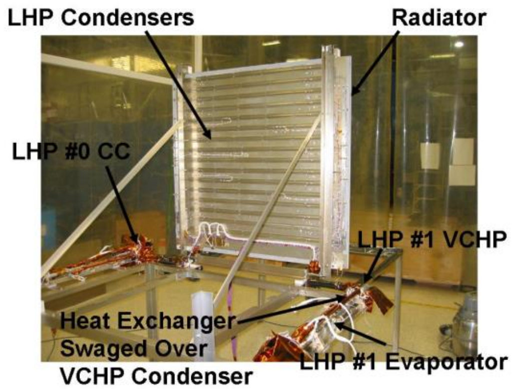

Figure 5. *Swift* BAT LHPs during Integration and Testing in 2003.

Each LHP CC has fully redundant operating heater circuits and non-operating heater circuits. The operating heater circuits are controlled by flight software to provide good temperature stability (approximately ±0.1°C) for the CC. The non-operating heater circuits are controlled by mechanical thermostats. To achieve a 45°C PPU baseplate operating temperature, which has a 5°C margin, an approximately 32°C CC temperature is needed. The redundant operating heater set point is 2°C lower, so that only the primary operating heater draws current during nominal operation. As a result, an approximately 25°C radiator temperature is required. The size of the radiator with Z93C55 conductive white paint, which has an absorptance of 0.37 and a hemispherical emittance of 0.88 for worst hot case, is approximately 1.28 m^2.

The primary non-operating heater mechanical thermostats close at -30°C and open at -25°C, and the redundant non-operating heater mechanical thermostats close at -35°C and open at -30°C. When the PPU is non-operating, only the non-operating heater circuits are enabled. The LHPs shut down and stop circulating the working fluid (propylene) to the radiator. As a result, there is no heat transfer from the PPU to the radiator. The above mechanical thermostat set points assure the PPU non-operating temperature to be warmer than -40°C after the LHPs shut down. Each LHP evaporator has startup heaters and over-temperature protection mechanical thermostats for starting up to assure the working fluid circulates before the PPU is powered on. In flight, the startup heaters are commanded on or off.

Fig. 6 shows how the PPU LHPs are accommodated. There is a gap between the PPU baseplate and radiator. If the LHP condensers are attached to the radiator backside, a 5 cm gap is adequate. If the LHP condensers are embedded in the radiator, a 2.5 cm gap is adequate. The PPU baseplate is extended on two sides for mounting the LHP evaporators. CCHPs are attached to the PPU baseplate and transfer heat to the LHP evaporators by conduction through the thermal contact interfaces. Except the LHP CCs, all the exposed surfaces of the LHPs, radiator backside and PPU are covered by MLIs. Note that LHPs are not affected by gravity during ground testing.

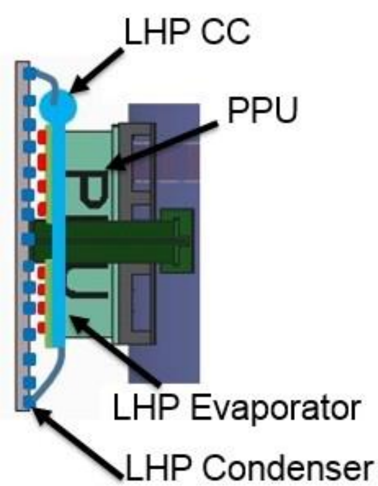

Figure 6. PPU LHP Accommodation.

Since the PPU radiator area is more than five times that of the PPU baseplate area, the backside of the PPU radiator could be utilized for radiating heat to space if it has a good view to space. This utilization reduces the physical size, and therefore mass, of the PPU radiator. For the thermal louver option, if the radiator backside is used for heat rejection, louvers on the both the front and back sides of the radiator will be needed.

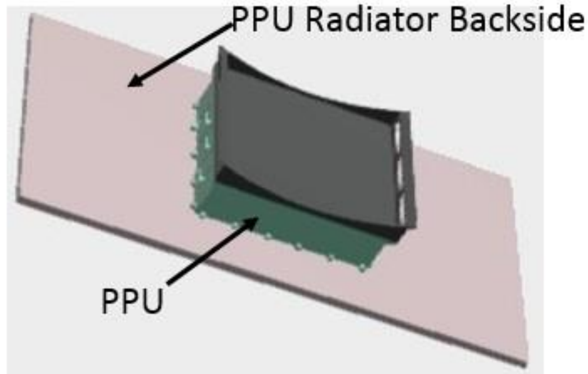

Figure 7. PPU Radiator Backside.

Like the *Swift* BAT LHPs, a variable conductance heat pipe (VCHP) is used on the LHP. The VCHP evaporator is thermally coupled to the LHP evaporator. A heat exchanger is swaged over the VCHP condenser to allow heat exchange between the VCHP condenser and LHP liquid return line. A small fraction of the PPU waste heat transfers from the LHP evaporator to the VCHP evaporator. This provides pre-conditioning of the propylene liquid before it returns to the LHP CC. The VCHP reduces the LHP CC operating heater power.

Based on *Swift* BAT, with a VCHP, each PPU LHP requires 15 W of operating or survival heater power for its compensation chamber. If the PPU exterior is insulated with MLI, it also leaks about 5 W to space through the MLI while it is non-operating at -40°C. The total survival heater power required for each PPU is 35 W. Therefore, LHPs reduce the PPU survival heater power by 148 W or 81%.

If a mission uses, for example, three ion thrusters and three PPUs, a total of six LHPs will be required for full redundancy. Under such a scenario, LHPs reduce the total PPU survival heater power by 444 W.

IV. Conclusion

This paper presents a thermal design concept of using LHPs to minimize the NEXT PPU survival heater power for solar system exploration missions. It reduces the survival heater power from 183 W to 35 W per PPU. The reduction is 81%. If a mission uses three ion thrusters and three PPUs, a total of six LHPs are required for full redundancy, such that the total PPU survival heater power is reduced by 444 W.

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